Impedance of LOFTI IIA Very-Low-Frequency Antennas in the Ionosphere

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ABSTRACT

The spacecraft of the LOFTI IIA transionospheric very-low-frequency (vlf) receiving experiment was fitted with relatively simple automatic instrumentation for periodic indication of vlf antenna admittance in the 10 to 18 kHz range. Analysis of part of the resulting data has shown the following:

1. The admittance of the vlf magnetic dipole (a D-shaped, shielded loop approximately equivalent in capture area to a 14-in.-diameter circular coil) was essentially unaffected by the change in environment of the spacecraft from the earth's surface to the ionosphere. Variations of local electron density in the ionosphere and change of antenna orientation relative to the geomagnetic field had no discernible effect.

2. The admittance of the vlf electric dipole (two 20-ft-long opposed whips) remained capacitive, but the apparent capacitance varied markedly as the spacecraft moved along its orbital path. As much as 10 to 20 times free-space value was indicated at altitudes shown by published typical data as likely regions of greatest electron density. At high electron-density levels, a two-to-one cyclic variation of capacitance was evident with change of dipole orientation relative to the geomagnetic field as the spacecraft rotated on its spin axis. At altitudes of likely low electron density, variation with spin decreased and the capacitance approached that expected in free space.

PROBLEM STATUS

This is a final report on one phase of the problem; work continues on other phases.

AUTHORIZATION

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IMPEDANCE OF LOFTI IIA VERY-LOW-FREQUENCY ANTENNAS IN THE IONOSPHERE

INTRODUCTION

Part of the instrumentation of the LOFTI IIA vlf receiving-satellite experiment of June and July 1963 was intended for determining the effects of the ionosphere on the admittance of the vlf antennas mounted on the spacecraft. A general description of the experiment as a whole and its instrumentation is given by Ref. 1, and much information developed in the subsequent data processing appears in Ref. 2. This report will treat only the vlf antenna-admittance instrumentation of the experiment and the most important characteristics obtained from processing the pertinent portions of the telemetry records.

ANTENNA INSTRUMENTATION

Figure 1 shows an exterior view of the LOFTI IIA spacecraft. The magnetic-dipole antenna (vlf loop) consisted of a 36-turn coil of 180/36 litzendraht (litz) inside a D-shaped aluminum tube, which served as the antenna's electrostatic shield. This coil was equivalent in aperture or pickup capability to a 14-in.-diameter circular loop. The electric-dipole antenna (vlf whips) consisted of two thin-wall hollow tubes formed by the curling of flat, prestressed beryllium tape unwound in orbit from two separate reels, each to a maximum length of 20 ft. This report will treat the data obtained with the whips at maximum extension, i.e., the 40-ft-dipole case.

The loop and the whip dipole were each provided with its own, separate vlf receiver and admittance-determination circuitry. The variations in apparent admittance of the loop in orbit could be determined by internal injection of cw calibration input of 10.2 and 18.0 kHz frequency. Variations of whip-dipole admittance could be determined similarly by internal cw injection at 16.917* and 18.0 kHz.

ATTITUDE INSTRUMENTATION

Two small squibs mounted atop the loop antenna, which were fired after the spacecraft was in orbit, initiated spacecraft spin. The spin rate, after full extension of the vlf whips, was about 15 rpm about an axis approximately parallel to the telemetry-dipole antenna (telemetry whips). The spin helped stabilize the spacecraft in orbit and also rotated the vlf antennas, so that the effect of antenna attitude in the earth's magnetic field on apparent antenna admittance could be observed.

The attitude of the spacecraft with respect to the geomagnetic field and a line to the sun was indicated by onboard magnetic and solar sensors. The two magnetic sensors (magnetometers) were automatically extended on a boom after nose-cone separation. They were, thereby, moved away from the spacecraft, to lessen the possibility of magnetic interference to or from the vlf instrumentation.

*To economize spacecraft volume and power, the whip receiver's local oscillator (LO_1) served as the source of the 16.917-kHz calibration signal.

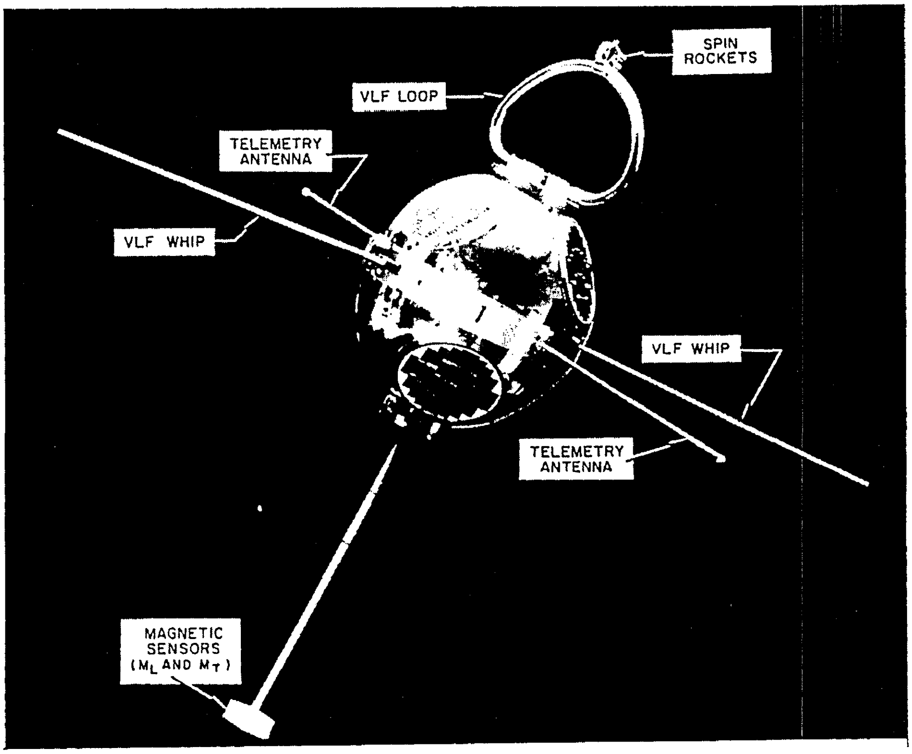

Fig. 1 – LOFTI IIA spacecraft with the vlf whips (electric dipole) partially extended

SPACECRAFT ORBIT

Figure 2 lists the initial orbital elements of LOFTI IIA and depicts the changing orientation of the vlf antennas as the spacecraft moved along its orbital path while rotating around its spin axis. The lifetime of the spacecraft was about 32 days.

ANTENNA ORIENTATION

Figure 3 depicts the contours of the geomagnetic field in cross-section and shows the variations of the spacecraft's magnetic-sensor indications as they might appear during one orbital period. When the spin axis (essentially the axis of the telemetry antenna, whips 2 and 4) was parallel to the local geomagnetic field, the output of the longitudinal sensor M_L would be maximum and that of the transverse sensor M_T practically zero. When the spin axis was essentially perpendicular to the geomagnetic field, the M_T variation would be maximum and that of the M_L close to zero.

Therefore, whenever the M_L indication in the telemetry data was very small or about zero, it could be assumed that the axis of the vlf whip dipole was then spinning from practically parallel to perpendicular to the geomagnetic field. Conversely, when M_L was maximum and M_T close to zero, it could be assumed that the axis of the vlf whip dipole was essentially perpendicular to the field irrespective of spin.

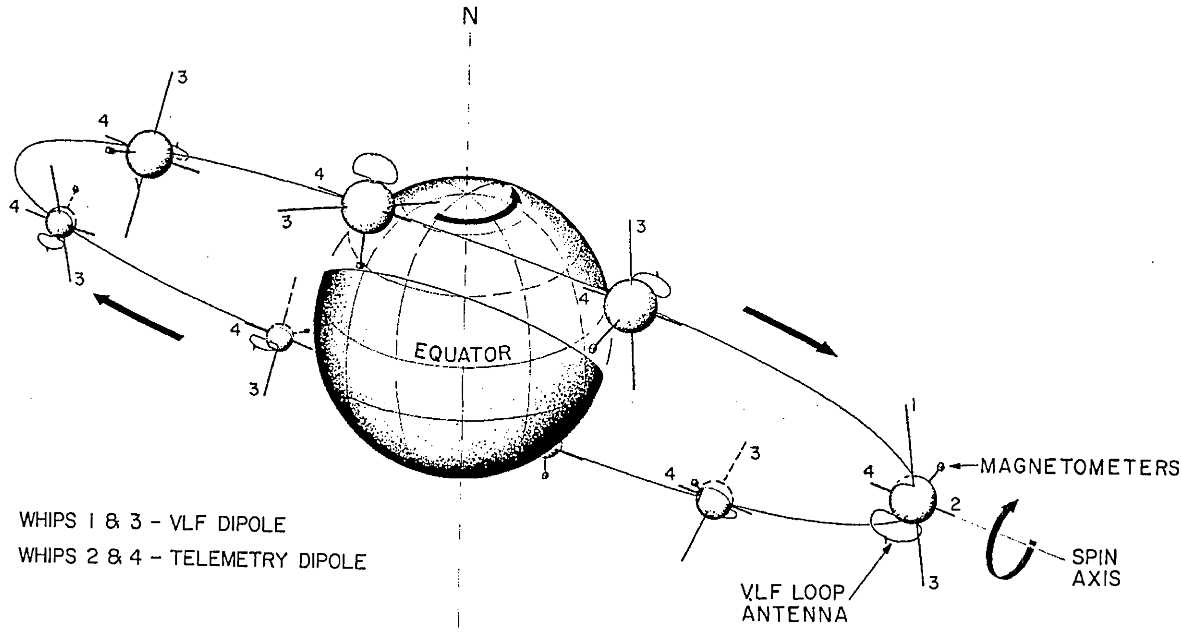

Fig. 2 – Variation of LOFTI IIA antenna orientation along the orbital path. The initial orbital elements of LOFTI IIA were an inclination of 70 degrees, an apogee of 925 km, a perigee of 170 km, and a period of 96 min.

ADMITTANCE OF THE MAGNETIC-DIPOLE ANTENNA

The loop inductance (943μ H) was part of a two-pole four-element network (Fig. 4) simultaneously resonant at 10.2 and 18.0 kHz. In-orbit loop admittance at these two frequencies was determined by observation of the two receiver outputs during periodic intervals of 10.2 or 18.0 kHz cw calibration input into the antenna circuit.

EFFECT OF ENVIRONMENT ON LOOP-CIRCUIT CHARACTERISTICS

A loop winding and a conductive (electrostatic) shield can be considered, in effect, as the secondary and primary, respectively, of a tightly coupled transformer. The secondary is usually tuned to resonance at a desired frequency by a capacitor of appropriate value. The shield (primary) cannot short-circuit the secondary despite the close magnetic coupling between them, because of an insulated gap. If the loop were immersed in a conductive medium, such as the ionosphere, this gap would be shunted by the ionized plasma. Since the effective admittance of such a medium can be much larger than that of free space, both the resonant frequency and the Q of the tuned secondary could be expected to change to a degree dependent on the characteristics of the plasma in the particular region.

The effect of shield-gap shunting was experimentally determined in the laboratory before the LOFTI IIA spacecraft was launched. Capacitors and resistors of a wide range of values were connected in turn across the gap in the shield. As shown by Fig. 5, a shunt susceptance of 0.5 mho (2-ohm capacitive reactance) or a conductance of 0.2 mho (5-ohm resistance) decreased the amplitude of loop-circuit response (i.e., the voltage appearing at the loop-coupling-circuit output terminals with calibration input) by 10%.

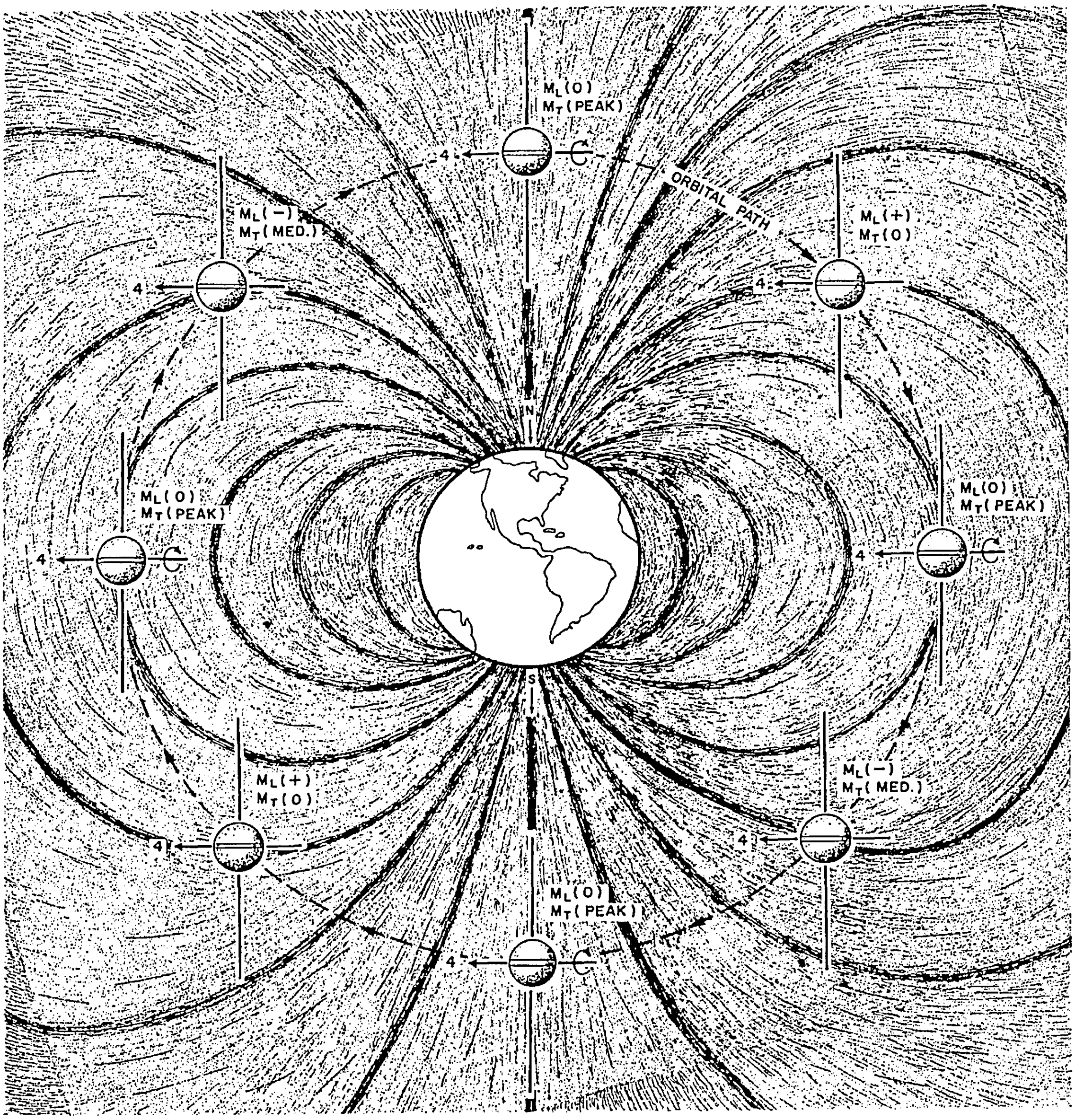

Fig. 3 – Variation of the magnetometer output with the spacecraft orientation in the geomagnetic field

The loop in-orbit admittance data from the spacecraft have been carefully examined in the telemetry records, and no evidence of shield-gap shunting has been found. Apparently, loop admittance in the ionosphere was not appreciably different from that measured on the ground, throughout the lifetime of the spacecraft.

EQUIVALENT IMPEDANCE OF THE ELECTRIC-DIPOLE ANTENNA

Figure 6 shows the free-space-series impedance components of an idealized 40-ft electric dipole at 18.0 kHz, calculated using formulas by Schelkunoff (3). The capacitive reactance X_c (approximately 300,000 ohms) is greater than the other components of the

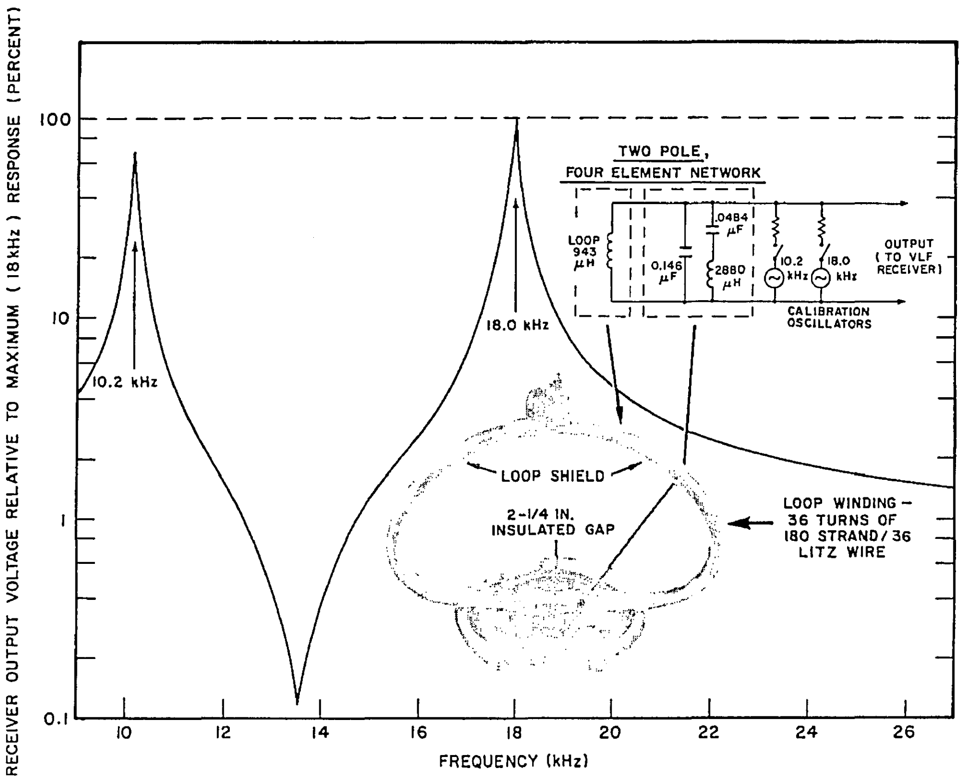

Fig. 4 – Frequency response of the loop system to constant-intensity radio field (terrestrial measurement)

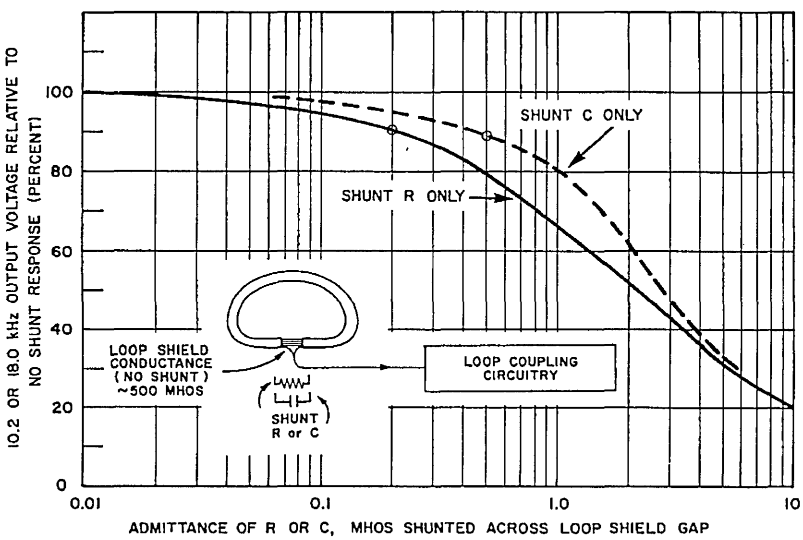

Fig. 5 – Effect of a shunt across the loop-shield gap

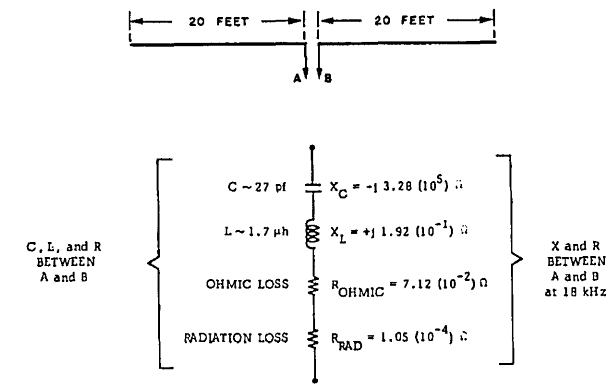

Fig. 6 – Computed free-space impedance components of a 40-ft dipole

impedance by six orders or more. It therefore appears that around 18.0 kHz, and in free space, such an antenna would appear to be essentially a low-loss condenser of about 27 pF.

However, the actual antenna, consisting of the two diametrically opposed 20-ft whips extending from the spacecraft, would not be electrically as simple as the idealized 40-ft dipole of Fig. 6. The approximately 2-ft-diameter body of the spacecraft separated the whips physically, interposing a curved common-ground plane of considerable area between their nearer ends. In effect, the spacecraft carried two 20-ft-long opposed monopoles that served as a dipole which would probably have somewhat less than 27-pF capacitance in free space (4).

DIPOLE-ANTENNA COUPLING

Each vlf whip was provided with a coupling network located inside the hull of the spacecraft (Fig. 7). In designing these networks, the likely minimum value of the monopole, or half-dipole, capacity, C_A, in orbit was assumed to be 75 pF, and the likely maximum was assumed to be 3000 pF. The coupling networks were identical and designed to resonate at 18.0 kHz, when C_A was 75 pF, and at 16.917 kHz, when C_A was 3000 pF.

While the spacecraft was in orbit, the whip-dipole-antenna-admittance determinations were made periodically at 16.917 and 18.0 kHz. The response of the whip-dipole network to 16.917-kHz cw excitation was indicated by the rectified radio frequency (rf) output, i.e., the direct current change of a detector. The response to the 18.0-kHz excitation was indicated by the 25-Hz i-f output of the receiver.

CALIBRATION OF THE DIPOLE-ANTENNA COUPLING CIRCUITS

Figure 8 shows the voltage output of the whip-dipole network with simultaneous shunting of the whip input terminals of the coupling networks by either identical external capacitors C_A or resistors R_A. The whips themselves were not connected in circuit. The determinations were made in the laboratory prior to spacecraft launch. C_A ranged in value from 0 to 10,000 pF, and R_A ranged from 10 megohms to 1000 ohms.

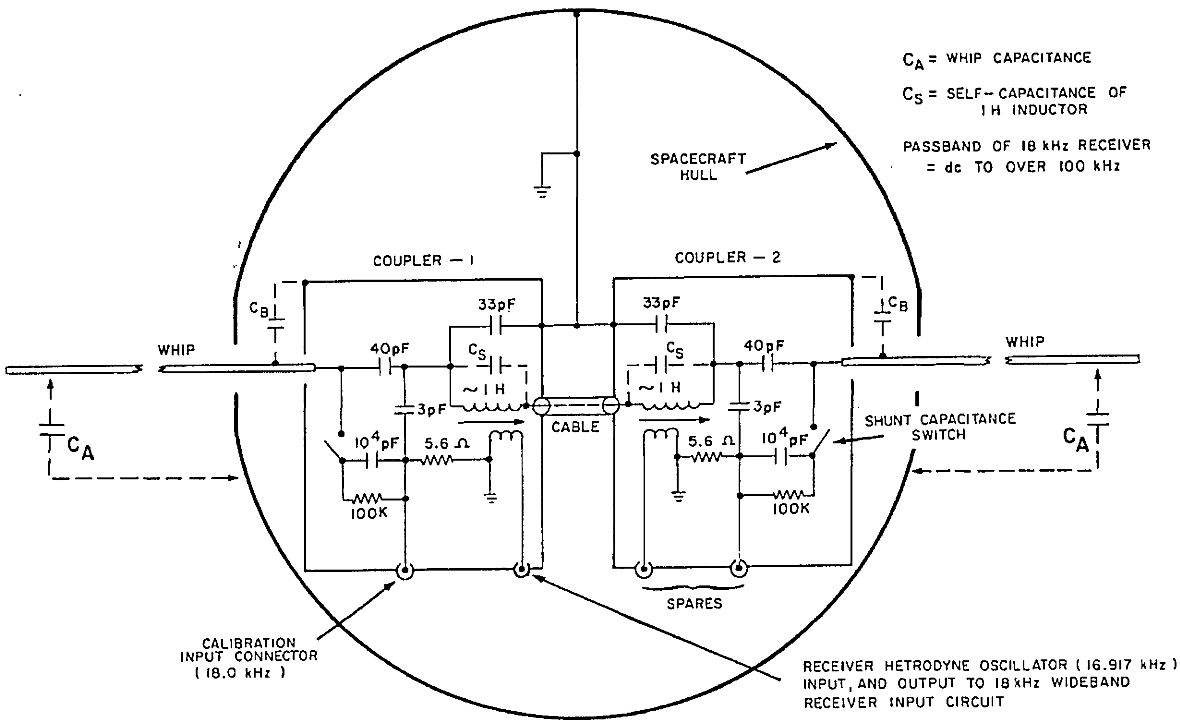

Fig. 7 – Vlf whip-dipole-antenna coupling network

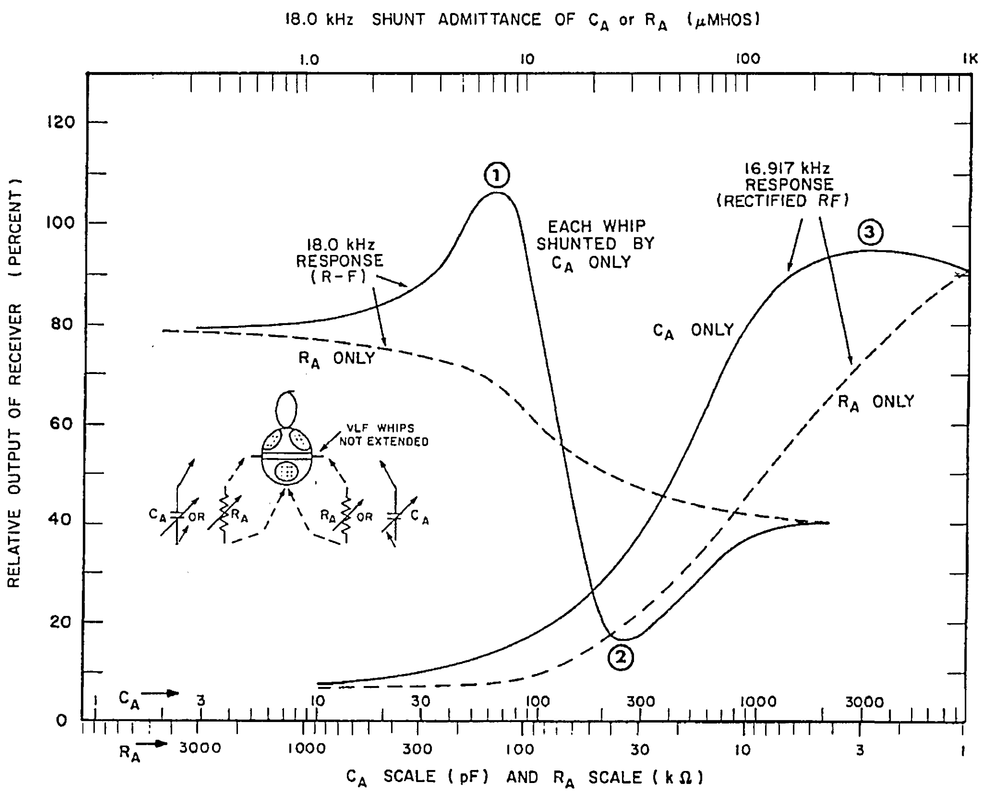

Fig. 8 – Effect of shunting vlf whip terminals with capacitance or resistance

The solid and dashed lines represent the effect of capacitance and resistance shunting, respectively, on antenna-network response (output voltage). It can be seen that both the total change and the rate of change of output (measurement resolution) were larger with capacitive shunting. The values at the inflection points (1, 2, 3) are of particular interest; these occur only with capacitive shunting. Resistive shunting (over the four-order range of the laboratory calibration) caused only a gradual decrease of response, with no sharply defined inflections. Occurrence of readings at point 1, 2, or 3 in the in-orbit data would therefore, tend to indicate that the dipole admittance was then essentially capacitive.

SIGNAL INTERFERENCE DURING ANTENNA ADMITTANCE MEASUREMENTS

Search of the LOFTI data records revealed that the 18.0-kHz admittance data for the vlf whip dipole in the nighttime ionosphere were almost always obscured by relatively very large 18.0-kHz vlf signals and noise from terrestrial sources. However, the 16.917-kHz data were not as seriously affected, probably because of larger injection voltage and lower sensitivity at that frequency.

DAYTIME ELECTRIC-DIPOLE ADMITTANCE

Whip-dipole calibration data at 18.0 kHz obtained during daylight passes were not so completely obscured by external signals. The additional attenuation of the ionized "D" layer in the sunlit part of the atmosphere was apparently sufficient to substantially decrease terrestrial vlf signal-and-noise intensity at the spacecraft. The minimum 18.0-kHz response (17%, region 2) could be seen occasionally in the data, indicating that dipole admittance was predominantly capacitive. If the plasma that surrounded the vlf whips had had appreciable resistive shunting effect, the response observed would likely have been in the 80 to 40% range. At no time was the 18.0-kHz response in the region 1 range when the spacecraft was in daylight. The 16.917-kHz calibration response occasionally approached region 3 values (where the whip-dipole network would resonate with C_A = 3000 pF) but was usually below this value except when the spacecraft approached the aurora regions at the higher latitudes.

NIGHTTIME ELECTRIC-DIPOLE ADMITTANCE

Figure 9 shows typical data from the records of a nighttime pass of the spacecraft over Panama at 217 to 236 km altitude. The five time frames shown are within a 3-min period at about 1 a.m. local mean time. Magnetic-sensor output is shown in the upper half of each frame. The changing value of apparent antenna capacitance, indicated by the 16.917-kHz response of the whip-dipole network, is marked in the lower half of each frame.

In frame $\boxed{1}$ of the sequence, the 16.917-kHz-output trace indicates a steady low value of admittance (response about 15%). Radio station NBA's 18.0-kHz signals and some vlf noise can also be seen. The antenna admittance appears to be essentially constant, even though the magnetometer-output traces indicate continual spin of the spacecraft. The low and invariant response, regardless of dipole orientation, may be interpreted as evidence of a relatively low level of electron density in that part of the ionosphere.

The dipole capacitance appears to be approximately 38 pF (C_A = 75 pF), which is about 40% greater than the calculated capacitance of the 40-ft dipole in free space. The observed

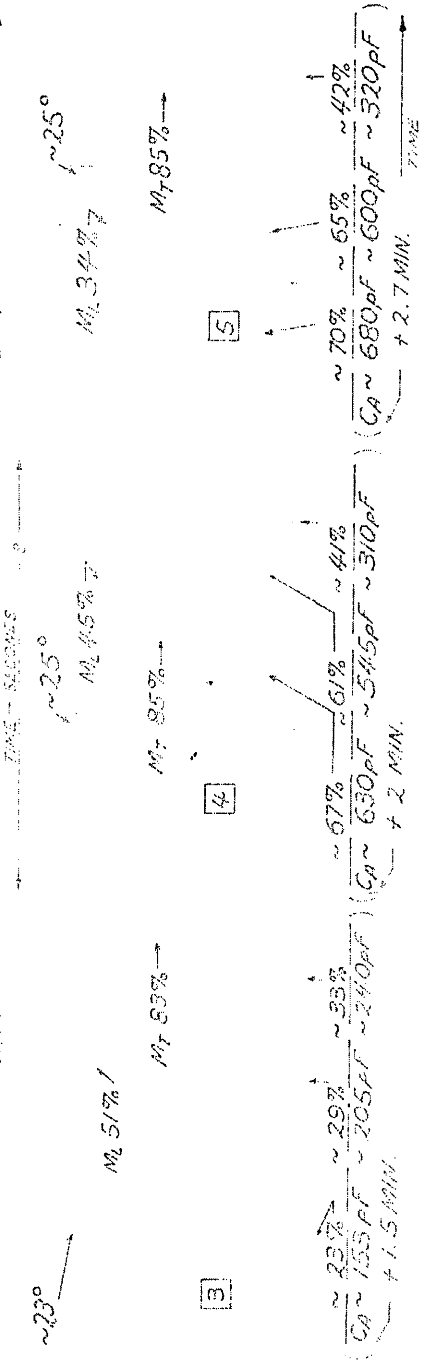

Fig. 9 – Magnetic-sensor and 16.917-kHz calibration response (nighttime pass (473P); 3-min segment around 1 a.m. local time; altitude of spacecraft was 217 to 236 km)

response is near the minimum obtained in the 16.917-kHz laboratory calibration (Fig. 8).* Similar low readings, indicating apparent capacitance to be not much greater than free-space value, occur frequently in the night data of the experiment whenever the spacecraft altitude was in the vicinity of 200 km.

In frame 2 of Fig. 9 (approximately 1 min later than frame 1), the response has increased to about 18% but still shows no apparent indication of dipole admittance variation due to changing orientation in the geomagnetic field. This reading represents a capacitance value somewhat greater than 100 pF.

In frame 3, about 1.5 min after the start of the sequence, the response has further increased and is beginning to vary at twice the spin rate. The appearance of this variation, the larger capacitance indicated by the higher response level, and the drop in M_L lead to the conclusion that the spacecraft has moved to a region of appreciably higher electron density and that its orientation relative to the geomagnetic field has changed. The minimum capacitance in the frame 3 interval is apparently near 155 pF, and the maximum is about 240 pF.

EFFECT OF ORIENTATION IN THE GEOMAGNETIC FIELD

All the data examined (day or night passes) show little effect of spacecraft spin on whip-dipole admittance when the apparent dipole capacitance approaches the free-space value. In frames 4 and 5 of Fig. 9, where the apparent capacitance approaches 10 times this value, the effect of change of antenna orientation relative to the geomagnetic field can be seen very clearly.

From study of the bibliography, it appears that the theoretical predictions of dipole admittance in a magneto-ionic medium do not completely agree. Most of the sources conclude that vlf dipole admittance should be maximum when the dipole axis is perpendicular to the geomagnetic field and minimum when parallel to the field, with a variation over several orders of magnitude, if direct contact to the medium is achieved, i.e., no plasma sheath. However, the experiment did not verify this prediction.

In frames 3, 4, and 5, the apparent capacitance of the antenna is not quite maximum when the M_T magnetometer reading reverses polarity (zero crossing) and is not quite minimum when the magnetometer reading is maximum. The time displacement between the magnetometer-output maximum and apparent capacitance minimum, stated in terms of relative phase, is about 25 degrees in these three frames. This effect may be ascribed to a number of possible causes, for instance, in some part to a plasma sheath such as forms around moving objects in the ionosphere (5). This sheath may be modified cyclicly to some degree as the potentials induced in the antennas and hull change with spacecraft spin and translation through the geomagnetic field.

The ratio of maximum-to-minimum capacitance appeared to be dependent upon electron-density and geomagnetic-field intensity but did not exceed a ratio of two-to-one in either day or night data. The variation in amplitude of the alternate capacitance maxima, shown in frames 4 and 5, was only evident in the nighttime data.

*Because of telemetry distortion and instabilities, the data resolution of the experiment was about ± 2%, which would translate into a possible capacitance range of 57 to 93 pF for a 15% response reading.

CHANGE OF ADMITTANCE WITH ALTITUDE

During the approximately 3-min sequence of Fig. 9, the spacecraft traversed a distance of about 750 naut mi, and its altitude increased from 217 to 236 km. As already mentioned, the large increase in apparent capacitance of the whip dipole indicates that the spacecraft moved, in this short time, from an environment of low electron density into one of relatively high electron density.

Local electron concentration was not specifically determined in the LOFTI experiments. Typical electron-density profiles of the nighttime ionosphere show that electron concentration increases rapidly with increase in altitude in the 215 to 240 km region. For instance, Ref. 6 indicates that an increase from about 10^3 electrons/cm^3 near 200 km to a maximum of about $2(10^5)$ electrons/cm^3 near 300 km might be expected. (Such a change is shown by the night electron density profile in a later figure.)

WAVE IMPEDANCE AND E/H RATIO IN SPACE

In a free-space environment, the field intensity of the magnetic component of a radio wave (as indicated in this case by loop signal output) is related to the corresponding electric-field intensity by the wave impedance of free space ($Z_0 = E/H = 120\pi$ ohms); i.e., $E = Z_0 H = 120\pi\ H$, where E is expressed in volts per meter (V/m) and H in amperes per meter (A/m). If both the loop and the whip-dipole circuits are tuned to the same signal frequency and are immersed in a medium which approximates free space, the loop-circuit-signal output voltage should equal the whip-dipole-circuit-signal output voltage, if the two antenna systems have about the same effective output impedance and the same effective height or aperture. If this is not the case, the two output voltages may be normalized or suitably equated for comparison purposes.

COMPARISON OF LOOP AND WHIP-DIPOLE-ANTENNA-SYSTEM SIGNAL OUTPUT

Although, as previously mentioned, strong terrestrial signals and noise interfered with nighttime 18.0-kHz whip-dipole-admittance determination, these signals were useful for intercomparison of loop and whip-dipole performance as signal collectors in the ionosphere.

Figure 10 compares the apparent field intensity of the 18.0-kHz signals as indicated simultaneously by loop and whip-dipole receiver output during the time frames shown in Fig. 9. The sensitivity of the loop system overall had previously been determined in the laboratory in terms of the microvolts per meter field intensity at the loop which would produce a given signal output. Because of measurement difficulty, the sensitivity of the whip-dipole system overall was computed. The apparent field intensity at the loop is stated in Fig. 10 in terms of the electric component of a free-space field, to allow direct comparison with the whip-dipole data.

In frame $\boxed{1}$, the apparent magnetic and electric components in microvolts/meter differ by only about 0.5 db. The spacecraft was moving at that time through a region in which the increase of vlf whip-antenna admittance over free-space value was relatively minor. From frame $\boxed{1}$ to frame $\boxed{2}$, the loop signal increased 4 db, while the whip-dipole signal decreased 12 db. Laboratory calibrations of whip-dipole-receiver sensitivity to change in antenna capacitance C_A, using a constant voltage signal applied in series with C_A, has indicated a maximum reduction of only 1 db in coupling-network signal output with capacitance change from 75 to 103 pF, as occurred between frames $\boxed{1}$ and $\boxed{2}$ of Fig. 9. Hence, the 15-db difference between loop and dipole signals in frame $\boxed{2}$ of Fig. 10 can be taken as representing a drop in electric-field intensity.

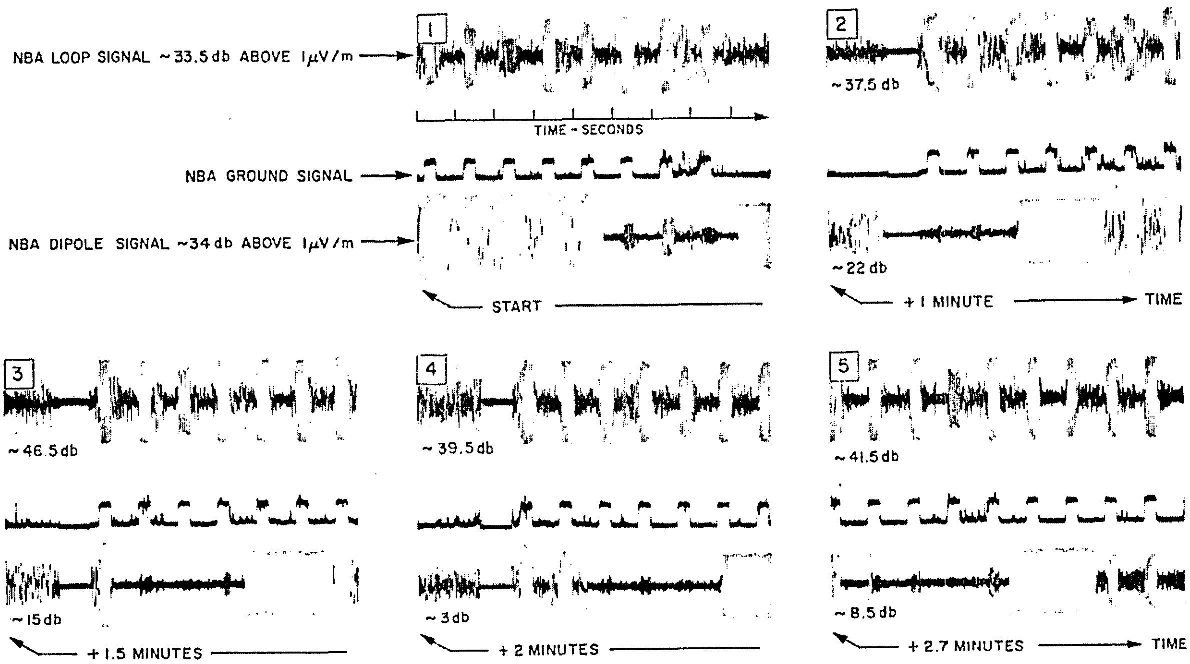

Fig. 10 - Field intensity in 3-min period covered by Fig. 9, as indicated by the loop and whip-dipole receiver output (the loop system calibrated on earth in microvolts per meter)

As previously mentioned, loop-circuit tuning appeared to be substantially unaffected throughout the LOFTI experiment by changes in local electron concentration; therefore, the 4-db increase in loop output must represent about that much increase in intensity of the magnetic component of the radio field. On this basis, it may be concluded that the ratio of E/H, and consequently, the wave impedance of the medium in which the two antennas were moving, had decreased substantially in the time period between frames 1 and 2, with still greater decrease in the following time frames (3, 4, and 5).

The salient information derived from the data of Figs. 9 and 10 is summarized in Fig. 11. A nighttime electron density profile for the altitude range 212 to 240 km, based on information in Ref. 6, is superimposed on the antenna-capacitance graph. The variations in relative whip-dipole and loop signal output shown by Fig. 11 are typical. Similar variations were observed throughout the data examined.

TYPICAL DAYTIME DATA

Figure 12 shows a sequence of whip-dipole calibrations made simultaneously at 18.0 and 16.917 kHz. The spacecraft was at about a 500-km altitude, in daylight. The "D" layer of the ionosphere, which would then be about 450 km below the spacecraft, probably served as the extra shield which allowed observation of low-level response in the calibration interval without excessive terrestrial vlf signal and noise interference.

The top trace in each of the three time frames shows the 18.0-kHz response (i-f). The actual 18.0-kHz dipole-admittance-determination interval (about 1.5 sec) immediately follows the voltage-calibration-reference interval marked 100%. The 18.0-kHz response observed in time frame 2 (17% of the reference (100%) response) could occur only with essentially nonresistive (capacity) shunting of the whip dipole. The simultaneous 16.917-kHz response is shown immediately below the 18.0-kHz data. The apparent capacitance values at the two frequencies, as derived from the Fig. 8 calibration, agree fairly well, considering that there was serious noise interference during the 18.0-kHz in-orbit calibration interval.

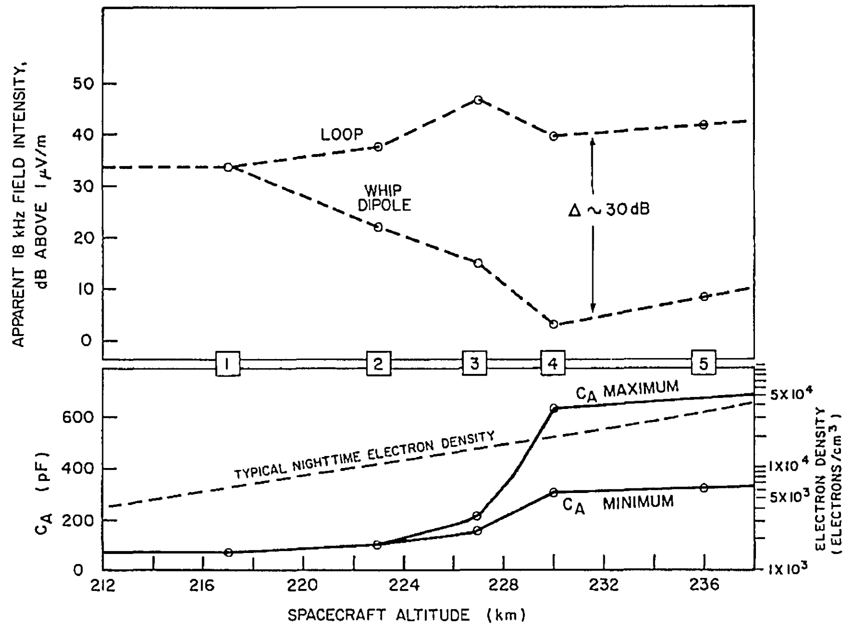

Fig. 11 – Apparent 18-kHz field intensity and the whip-dipole capacitance during period covered by Fig. 9 (3 min of nighttime pass 473P).

COMPARISON OF DAY AND NIGHT ADMITTANCE OF THE WHIP DIPOLE

Figure 13 presents a comparison of 16.917-kHz day and night data at essentially the same altitude (~375 km) and for the condition of the dipole spinning from parallel to perpendicular to the geomagnetic field ($M_L = 0$). This is the orientation relative to the field for which dipole-admittance change should theoretically be maximum. The maximum variation observed under this condition in the entire experiment was found to be less than 2 to 1. In the upper half of the figure (day), calibration response is near the Fig. 8 region 3 value. The apparent antenna capacitance ranges from about 600 to about 930 pF.

In the calibration period marked 4 sec in Fig. 13, the inboard end of each of the two whips was shunted to the spacecraft hull by a 10,000-pF capacitor. If the admittance of the antenna without this shunt was in fact capacitive, the effective capacitance in the antenna circuit during the 4-sec shunt interval would be 10,600 to 10,930 pF, and the 16.917-kHz response during this time should be about 90% relative to the reference value. The reading actually observed in Fig. 13 is typical. This result and the small superimposed cyclic variation on it, which is synchronous with the following unshunted interval, affords further confirmation of the original assumption that the antenna is, in effect, a condenser with negligibly low loss.

VARIATION OF VLF DIPOLE ADMITTANCE WITH THE SPIN AXIS PERPENDICULAR TO THE GEOMAGNETIC FIELD ($M_L = 0$)

During both the day and the night period of the data of Fig. 13, the spin axis of the spacecraft was approximately perpendicular to the geomagnetic field. This orientation is indicated by the very small output of the M_L magnetic sensor in the two time frames

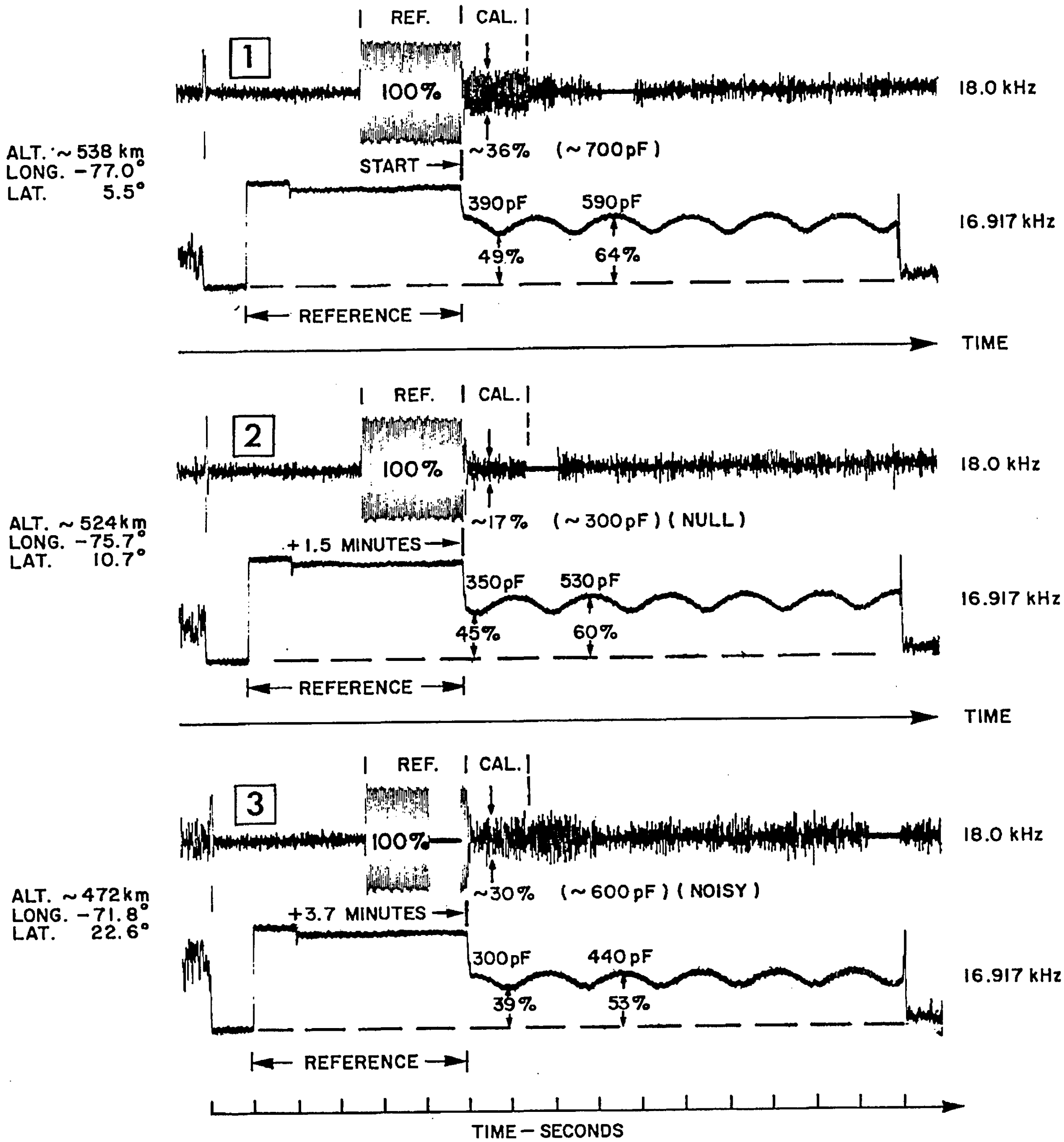

Fig. 12 – Comparison of simultaneous 18.0 and 16.917 kHz whip-dipole calibrations (18-kHz trace: IF output of receiver and 16.917-kHz trace: rectified output)

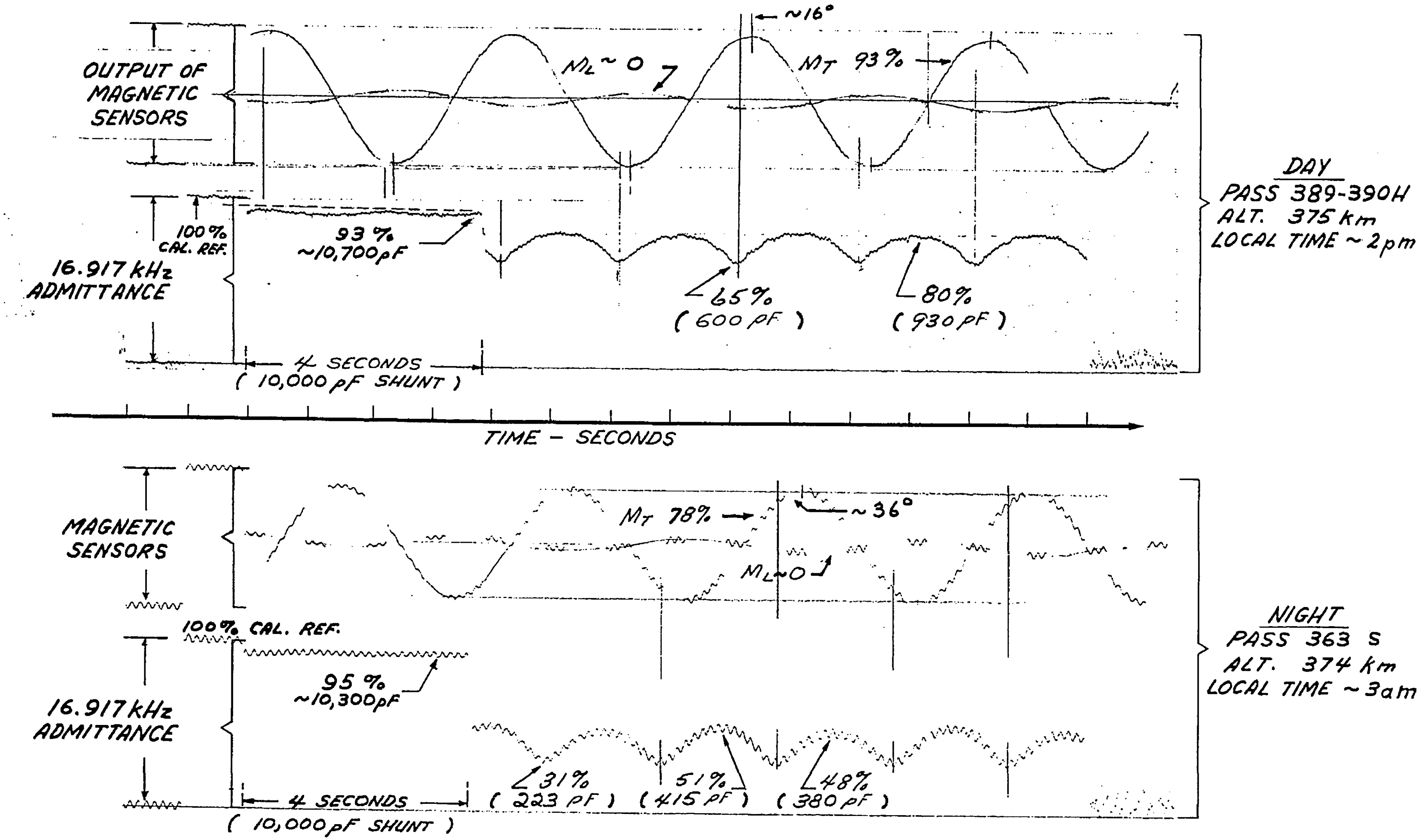

Fig. 13 - Comparison of 16.917-kHz calibration data, day and night, at same altitude, with the spin axis nearly perpendicular to the geomagnetic field. (Note: The ripple in the nighttime data is due to a mechanical defect in the tape recorder used at the telemetry receiving station.)

and the much larger output of the M_T sensor.* Twice during each rotation of the spacecraft, the orientation of the vlf whip-dipole axis would be changing from approximately parallel to approximately perpendicular to the field.

The theoretical sources previously mentioned would indicate that, if the whip-dipole axis had been exactly parallel to the geomagnetic field at the time of closest coincidence, the antenna admittance would be minimum; a quarter cycle later, with the antenna axis perpendicular to the field, the admittance would be maximum.

As in Fig. 9, the admittance minima do not quite coincide in time with the magnetometer maxima, the displacement being larger in the night data (36 degrees) than in the day data (16 degrees). Similar displacements were found in all the data obtained in the experiment, the larger value always occurring at night. The displacement observations could provide much further information on antenna attitude and orientation in the geomagnetic field; however, this aspect of the experiment was not studied in detail because of time and manpower limitations.

VARIATION OF VLF DIPOLE ADMITTANCE WITH THE SPIN AXIS PARALLEL TO THE GEOMAGNETIC FIELD ($M_T = 0$)

Figure 14 shows day and night admittance data (at 423 and 230 km altitude, respectively) at times when the spacecraft's spin axis was about parallel to the geomagnetic field. The axis of the vlf dipole was then essentially continuously perpendicular to the geomagnetic flux throughout the spin cycle. Its apparent capacitance should then be maximum for the particular electron concentration in the environment and should show practically no variation due to spacecraft spin.

It can be seen that the apparent capacitance is rather small in both cases. The capacitance values differ by a factor of somewhat more than 2. During the daytime pass, the spacecraft was over Santiago, Chile, in the winter season when electron density would be least and at an altitude somewhat above the likely region of highest electron density. During the nighttime pass, it was over Hawaii during the summer season but at an altitude at which electron density could be expected to be very low. The apparent capacitance C_A here approached the free-space value.

VARIATION OF APPARENT CAPACITANCE WITH ALTITUDE

Figure 15 summarizes a large amount of data showing the apparent capacitance of the vlf whip dipole, when the spacecraft was in daylight, plotted against altitude. The shaded part of the graph defines the area in which the averaged values for several hundred passes observed in various parts of the world lie. The least-value (minimum-minimum or min. min.) boundary approaches free-space value at the higher altitudes (600 km) but is greater elsewhere. The highest-value (maximum-maximum or max. max.) boundary has a profile similar to that of the typical daytime electron-density curve (6), which is shown as an overlay.

*With the spacecraft spinning exactly on the telemetry dipole axis and with that axis exactly perpendicular to the geomagnetic flux lines, the M_L sensor theoretically should produce zero output and the M_T sensor a maximum sinusoidal output. That this ideal alignment was not quite achieved in the time frames of Fig. 13 is evident from the slight trace of sinusoidal output from the M_L sensor, an effect observed in all cases. A displacement of the spin axis by about 6 degrees from the telemetry antenna axis is indicated by the sensor readings.

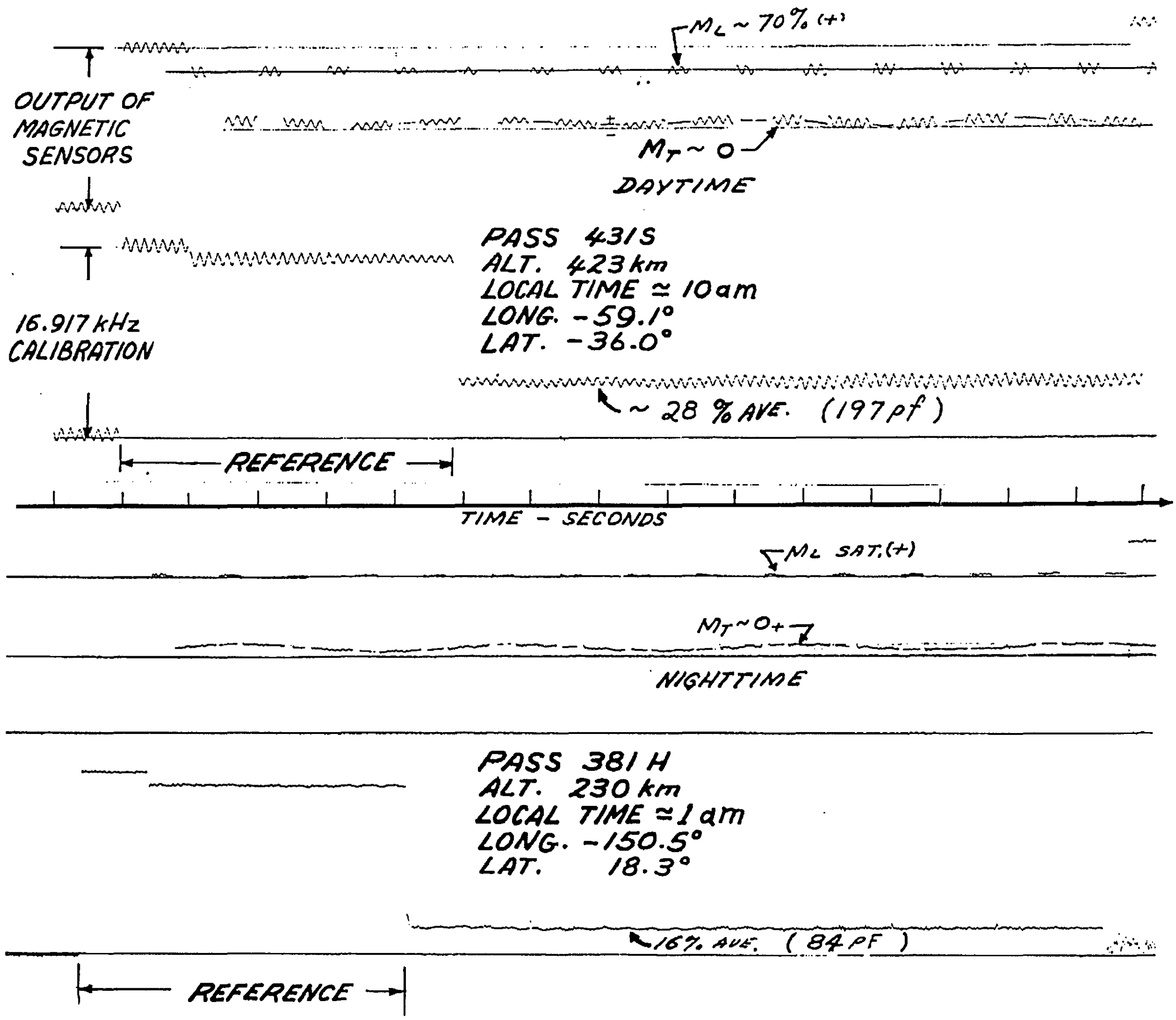

Fig. 14 - Comparison of 16.917-kHz calibration data, day and night, with the spin axis nearly parallel to the geomagnetic field. (Note: The ripple in the daytime data is due to the tape recorder.)

It is evident that electron density and apparent capacitance are correlated. The large spread in capacitance value between max. max. and min. min. at any particular altitude on the graph is indicative of the wide variation in ionization encountered by the spacecraft as it moved along its orbital path.

Figure 16 is a similar graph for several hundred night passes. Here also the max. max. boundary appears to be quite closely related to the typical electron-density profile.

CONCLUSIONS

From the data presented above, it can be concluded that

1. The admittance of a magnetic-dipole (loop) antenna at vlf-band frequencies is not substantially affected by change of antenna location from the terrestrial surface to an ionospheric environment.

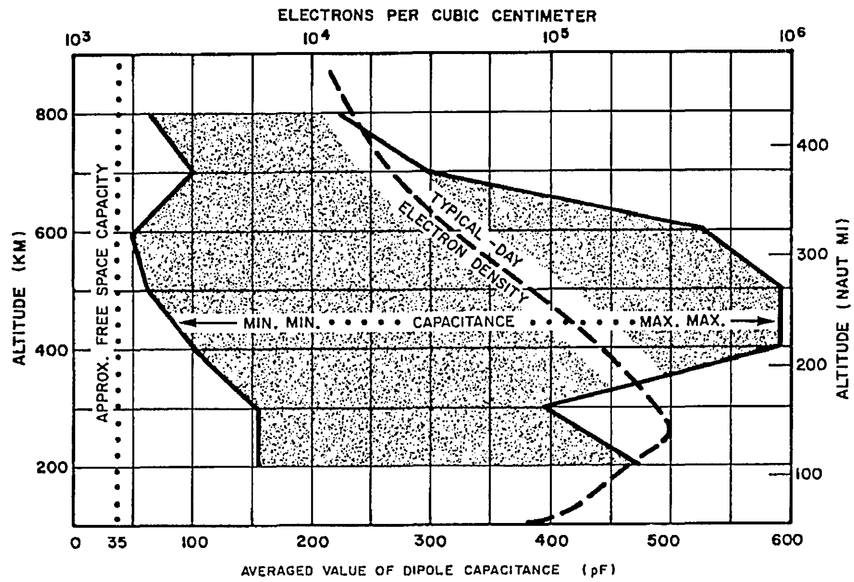

Fig. 15 – Summary of daytime vlf whip-dipole capacitance data

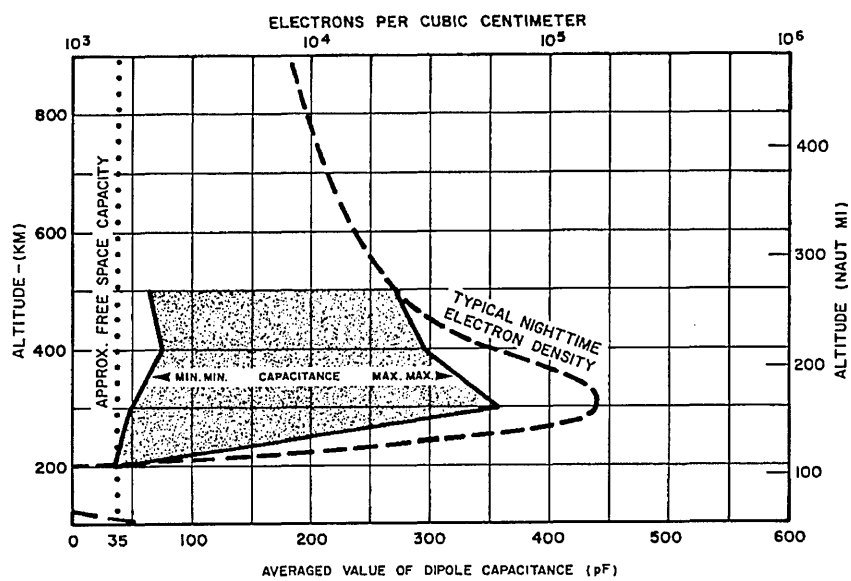

Fig. 16 – Summary of nighttime vlf whip-dipole capacitance data

2. The admittance of an electrically small electric (whip-dipole) antenna operating in the vicinity of 18.0 kHz in the ionosphere is predominantly capacitive.

3. The apparent capacitance of the LOFTI IIA electric-dipole antenna increases with increase of electron density (concentration) in the environment, to as much as 10 or 20 times its free-space capacitance.

4. The orientation of an electric dipole relative to the earth's magnetic field affects its apparent capacitance substantially when the electron density exceeds some minimum value. The maxima and minima of apparent capacitance are generally displaced from exact perpendicular and parallel dipole orientations, respectively, in the geomagnetic field, perhaps as a result of plasma-sheath interaction. The variation with change in orientation is not more than two-to-one.

RECOMMENDATION

The results reported here in brief are indicative of antenna characteristics in the ionosphere and should not be considered comprehensive. The antenna calibration instrumentation in the spacecraft was necessarily rudimentary, a factor which has made data analysis difficult. In view of the intended use of the derived information for design of a vlf transmitting experiment, the effects of geographical latitude and various other parameters have not been isolated. It is therefore recommended that spacecraft in future vlf satellite experiments be provided with instrumentation for direct, accurate, and (in so far as possible) continuous in-orbit determination of all components of vlf antenna impedance (reactance, ohmic resistance, radiation resistance, etc.).

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13. ABSTRACT

The spacecraft of the LOFTI IIA transionospheric very-low-frequency (vlf) receiving experiment was fitted with relatively simple automatic instrumentation for periodic indication of vlf antenna admittance in the 10 to 18 kHz range. Analysis of part of the resulting data has shown the following:

1. The admittance of the vlf magnetic dipole (a D-shaped, shielded loop approximately equivalent in capture area to a 14-in.-diameter circular coil) was essentially unaffected by the change in environment of the spacecraft from the earth's surface to the ionosphere. Variations of local electron density in the ionosphere and change of antenna orientation relative to the geomagnetic field had no discernible effect.

2. The admittance of the vlf electric dipole (two 20-ft-long opposed whips) remained capacitive, but the apparent capacitance varied markedly as the spacecraft moved along its orbital path. As much as 10 to 20 times free-space value was indicated at altitudes shown by published typical data as likely regions of greatest electron density. At high electron-density levels, a two-to-one cyclic variation of capacitance was evident with change of dipole orientation relative to the geomagnetic field as the spacecraft rotated on its spin axis. At altitudes of likely low electron density, variation with spin decreased and the capacitance approached that expected in free space.

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